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GENERATION OF A CONJUGATE WAVE FROM A WEAK SIGNAL.

FINAL REPORT

by

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To correct for focus distortions that arise when laser light is focused on a target through a turbulent medium, we had proposed to generate a compensating wavefront by means of optical parametric amplification (OPA). This report describes our efforts toward this end.

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RESEARCH OBJECTIVES

A problem that occurs in many applications of high-power lasers is that, when laser light is focused on a target through a turbulent medium, its wavefront is distorted and a degraded focus results. One approach to correcting distortions is to use active optics, whereby feedback from a point on the target provides information that in turn is used to compensate for the distortion by modifying the optics of the input beam.

We proposed an alternative to the active optics approach, namely, the generation of a compensating wavefront by means of optical parametric amplification (OPA). An advantage of OPA is its nearly instantaneous response time.

To generate the compensating wavefront we developed a device for generating a conjugate wave from a weak signal using three-wave and four-wave mixing directly in a laser. Prior to the present contract year, we and others had used a four-wave device that met all requirements for successful operation, and we had developed and used for preliminary tests a three-wave device that met all requirements except that of phase matching at 90°. In all cases, the system used a YAG laser at 1.06 μm.

The proposal for the present year's work set forth the following objectives.

1. To develop and optically analyze the 0.945-μm YAG $LiSO_4 \cdot H_2O$ crystal system as a bench-top model of a working optical conjugator using three-wave mixing. The same wavefront- and amplitude-sensing techniques would be used as before.

2.   To optically analyze the four-wave device in the same fashion as the three-wave device, and to compare these two methods of compensation.

3.   To quantify how the three-wave system is degraded when the 90° phase-match criterion is not met.   This would help specify the materials criterion in more detail.

4.   To continue to be useful to the efforts at AFWL and SAI in the search for 10.6-μm materials.

ACCOMPLISHMENTS OF THE RESEARCH EFFORT

To understand what was done this year, it is useful to review the recent developments in the problem to see how what we have done fits into the overall picture. Two mechanisms have been seriously considered for conjugation: three-wave mixing and four-wave mixing.[1] The U of A group is the only one involved in exploiting the first mechanism, and a number of groups, including ours, have pioneered in the second. Because in theory the three-wave mixing is subject to a number of limitations, our group has been concerned with the question of the quality of the phase conjugate. In addition, we have made, for the most part, direct, quantitative measurements of wavefronts (as opposed to "good" focal spot measurements). This is the easiest experiment for the case of conjugates generated in transmission, which is the case we typically investigate. This geometry is the only possible one for quadratic nonlinearities and is the simplest case with cubics. One key development that is of significance in generating conjugates at 1.3 μm is the use of semiconductors near the band gap. These provide extremely large nonlinearities that are significantly more efficient than all but the most extreme second-order nonlinearities. If one works too close to the band gap, then one has high absorption that decreases efficiency, and one is susceptible to thermal nonlinearities. Hence, the best operating point is chosen off one resonance where the nonlinearity is dispersive.

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1. J. E. Midwinter and F. Zernike, Applied Nonlinear Optics (Wiley, New York, 1973).

The problem with all dispersive cubics is that the nonlinear process is always accompanied by self-focusing. As is well documented by the laser fusion effort, self-focusing has the unfortunate property that it converts low-spatial-frequency amplitude perturbations into high-spatial-frequency phase perturbations with an attendant loss of power on target. If one takes a naive view of the problem, one can easily see that the phase disturbance is given by the square root of the efficiency. Taking, arbitrarily, a $\lambda/10$ limit to the allowed self-focusing, this permits an efficiency on the order of 10%. However, in semiconductors, the electrons and holes are highly mobile, which means that the efficiency will be reduced, while the self-focusing is unaffected.

After the submission date of last year's proposal, it was found that pure silicon has an effective conjugation at 1.06 μm. Since semiconductors are of major interest for NLO at 1.3 μm, we took the position that it was essential that we test silicon at 1.06 μm and check the optical quality of the conjugate. We have succeeded in applying our conventional techniques to this case, and have found that silicon is, as expected, at least as good as the quadratic systems and is very much easier to use. However, there are no easily used conventional interferometric techniques that are capable of measuring the level of self-focusing considered here. There is no point in considering very complex experiments, since one will be forever concerned as to whether the result is an artifact of the measurement. The doubling interferometers, which we have developed purely by accident as a consequence of trying to exploit conjugate-wave generation as a wavefront detection scheme, have enabled us to make simple interferometers that perform the task of measuring low-grade self-focusing very

well. Since these are novel techniques, we have been cautious about interpreting the results. Nonetheless, these show that self-focusing is a much more severe problem than would be expected on the basis of simple theory.

With this as a background, let us summarize our efforts for this contract year.

A. Development of Capabilities at 1.3 μm

We have had mixed success here. One key problem has been the self-lasing of our YAG laser, which has prevented us from operating at wavelengths other than 1.06 μm. We believe this is due to the peculiar design of our laser head. We have been trying to locate a supplier who can provide a conventional laser head, but YAG laser design has changed so much in the past nine years that we cannot use our 1971 model power supply without substantial rewiring. We have revived a pulsed dye laser with the primary purpose of using it to pump an iodine laser, hence obtaining the same wavelength as the chemically pumped iodine. So far, the dye laser has performed extremely poorly, providing only 10 to 20 shots between servicings.

We have had greater success in identifying $Gd_xTb_{2-x}(MoO_4)_3$ (we call this GTM) as a candidate for Type II noncritically phase-matched (NCPM) doubling at 1.3 μm. The optical properties of the pure $(x = 0,2)$ crystals are known, and the NCPM wavelengths lie on each side of 1.3 μm. One can temperature-tune the case $x = 2$, and it is reasonable to suppose that the others are the same. The crystal undergoes a phase transition near 150°C, so the tuning range of each mixture is small. Nonetheless, several

mixtures have been grown, and although their optical properties have not been studied, there is a reasonable chance that one will work. We have recently discovered a commercial supplier of the pure materials, and a private source of supply for $x = 1$. We are currently discussing the possibilities of joint efforts with these suppliers to develop an appropriate mix.

B. Studies in Silicon

This study has already been treated in the introduction and has resulted in two conclusions. We find that four-wave mixing in semiconductors is both superior to and easier than three-wave mixing in crystals. This is due to the very high nonlinear coefficient, which allows one to use very thin (0.25-mm) materials. Unfortunately, these have very large self-focusing ($\lambda/2$ sag is associated with a 1% efficiency). That makes them very dubious candidates at 1.3 μm. We have noticed sample-to-sample variation in the results and we are most anxious to pursue this further. We are aware that the only other materials development effort for NLO at 1.3 μm at AFWL involves semiconductors, and our studies are hence extremely timely. Our results are summarized in a paper to be published.[2]

C. Studies of High-Gain OPAs in Transmission

It was predicted many years ago that the angle-phase-match ($\Delta kL \lesssim \pi$) criterion in high-gain optical parametric amplifiers is less severe than predicted by small-gain formulas. This has recently been confirmed

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2. F. A. Hopf, A. Tomita, G. Al-Jumaily, M. Cervantes, and T. W. Liep-mann, "Phase conjugation by degenerate four-wave mixing in silicon," submitted to Optics Communications. [Abstract on p. 11.]

experimentally.[3] We have performed a calculation[4] on high-gain conjugation that shows that a similar effect occurs with the noncollinear phase-mismatch that is the source of the distortion[5] of the conjugate when generated in transmission (that is, as must be done with three-wave mixing, and which is the easiest configuration in four-wave mixing). We find that the distortion is decreased by high gain (high yield). This is exactly the opposite from the semiconductor case, in which self-focusing worsens as the yield increases.

D. Conjugate Interferometers

As a direct outgrowth of the previous work, we did a theoretical study[6] of the use of conjugate-wave generation as a means of diagnosing wavefronts. These have the properties of (a) being sensitive to small ($\sim\lambda/20$) wavelength changes, (b) providing high contrast even when the signal intensity is variable, and (c) yielding easily understood and quantifiable interference patterns. The simplest versions of the interferometer use three-wave mixing, which can be done with either Type I or Type II crystals. For cw operation, Type II is preferable; hence the development of GTM is directly applicable here. To make a decent proof-

3. R. Baumgartner and R. L. Byer, Tenth International Quantum Electronics Conference, Digest of Technical Papers, 688, 1978.

4. Frederic A. Hopf, "Optical distortion in phase conjugation in high-gain three-wave mixing," J. Opt. Soc. Am. 70(11): 1379-1381, Nov. 1980. [See p. 10]

5. F. A. Hopf, A. Tomita, K. H. Womack, and J. L. Jewell, "Optical distortion in nonlinear phase conjugation by three-wave mixing," J. Opt. Soc. Am. 69(7): 968-972, July 1969.

6. Frederic A. Hopf, "Interferometry using conjugate-wave generation," J. Opt. Soc. Am. 70(11): 1320-1323, Nov. 1980. [Abstract, p. 10.]

of-concept experiment, we need to make a high-efficiency doubling step, which is beyond the capability of our laser.

E. Doubling Interferometers

These have been experimental efforts whose results are too extensive to be summarized here; the main results are presented in two papers.[7,8] The application of these to self-focusing in silicon has already been noted.

F. Conjugate Wave Generation at 0.945 μm

We are, by now, convinced that our laser is not suited to operating at this line. We have borrowed a laser head from Stanford University to use at this wavelength. All other elements of this experiment are ready for use.

G. Studies of Bistability

Although optical bistability plays no role in this contract, it utilizes the same resonantly enhanced cubic nonlinearities as does phase conjugation. We have kept up a very small theoretical effort in this area as a means of maintaining contact with developments in that field. This effort resulted in a paper[9] that is included here for completeness.

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7. F. A. Hopf, A. Tomita, and G. Al-Jumaily, "Second-harmonic interferometers," Optics Letters 5(9): 586-588, Sept. 1980. [Abstract, p. 10.]

8. F. A. Hopf, A. Tomita, G. Al-Jumaily, M. Cervantes, and T. W. Liepmann, "Second-harmonic interferometers II," submitted to Optics Communications. [Abstract, p. 11.]

9. F. A. Hopf and S. A. Shakir, "Frequency switching in dispersive optical bistability," to be published. [Abstract, p. 11.]

H. Studies in Germanium

This is an effort in which most of the work is done at North Texas State University. Our involvement is on a consultant basis, and our interest lies in the fact that germanium is an absorptive cubic that may yet prove interesting for conjugation. A paper coming out of this effort is included here.[10] We intend to greatly expand this collaboration, since by using the picosecond facility at North Texas State we will be able to understand self-focusing in semiconductors in much greater detail.

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10. A. L. Smirl, T. F. Boggess, and F. A. Hopf, "Generation of a forward-traveling phase-conjugate wave in germanium," Optics Communications 34(3): 463-468, Sept. 1980. [Abstract on p. 10.]

CHRONOLOGICAL LIST OF WRITTEN PUBLICATIONS

The following papers have been published or are to be published, as a result of this year's contract work. Abstracts are included with the titles to provide more information about the coverage.

F. A. Hopf, A. Tomita, and G. Al-Jumaily, "Second-harmonic interferometers," Optics Letters $\underline{5}$(9): 386-388, Sept. 1980.

> Experiments on interferometers based on the second-harmonic generation of light from phase-matched crystals are described. This technique has potential applications for transmission tests of semiconductors and for contouring the surface of a three-dimensional object with fringes corresponding to wavelengths much larger than that of visible light.

A. L. Smirl, T. F. Boggess, and F. A. Hopf, "Generation of a forward-traveling phase-conjugate wave in germanium," Optics Communications $\underline{34}$(3): 463-468, Sept. 1980.

> In this communication, we report the generation of a picosecond forward-traveling phase-conjugate wave at 1.06 μm in thin germanium samples by degenerate four-wave mixing. At this wavelength, the conjugate wave is produced by diffraction of a pump from an absorption grating produced by <u>direct</u> absorption of pump and signal pulses. We measure and discuss the transient effects caused by the finite duration of the nonlinear material response.

Frederic A. Hopf, "Interferometry using conjugate-wave generation," J. Opt. Soc. Am. $\underline{70}$(11): 1320-1323, Nov. 1980.

> Interferometers based on conjugate-wave generation using three- and four-wave mixing are described theoretically. They are shown to be self-referencing and sensitive to small changes in the phase front.

Frederic A. Hopf, "Optical distortion in phase conjugation in high-gain three-wave mixing," J. Opt. Soc. Am. $\underline{70}$(11): 1379-1381, Nov. 1980.

> Optical distortion of phase conjugates made in high-gain degenerate, optical parametric amplifiers (OPA) using three-wave mixing is discussed theoretically. The distortion is shown to be less severe than predicted by low-gain formulas. This result applied also to four-wave OPA's in transmission configurations.

F. A. Hopf, A. Tomita, G. Al-Jumaily, M. Cervantes, and T. W. Liepmann, "Phase conjugation by degenerate four-wave mixing in silicon," submitted to Optics Communications.

The performance of phase conjugation by degenerate four-wave mixing in silicon was tested using an interferometric technique. An optical distortion due to self-defocusing was observed and measured to be a quarter wave at a peak energy of 30 mJ/cm^2. This result was obtained using recently developed nonlinear optical interferometers based on SHG.

F. A. Hopf, A. Tomita, G. Al-Jumaily, M. Cervantes, and T. W. Liepmann, "Second-harmonic interferometers II," submitted to Optics Communications.

Experiments on interferometers based on second harmonic generation of light are described. These make use of the distortions of phase and amplitude produced by the phase mismatch of angle-matched crystals to provide information. The interferometers are directly sensitive to small wavefront tilts and do not require additional reference wavefronts.

F. A. Hopf, A. Tomita, and T. W. Liepmann, "Quality of phase conjugation in silicon," submitted to Optics Communications.

F. A. Hopf and Sami A. Shakir, "Frequency switching in dispersive optical bistability," to be published.

The theory of dispersive optical bistability is considered with special attention to the cavity dynamics when the input frequency is changed. Changes in the conventions used in the slowly varying amplitude and phase approximation (SVEA) are necessary. The distinction between phase- and frequency-switching is shown. Preliminary results are discussed.

PROFESSIONAL PERSONNEL ASSOCIATED WITH THE RESEARCH EFFORT

Frederic A. Hopf, Associate Professor

Mike Jacobson, Research Specialist

Aki Tomita, Graduate Student

Till Liepmann, Graduate Student

DEGREE AWARDED

Aki Tomita, PhD (passed September 1980)
   Dissertation: "Nonlinear Optical Phase Conjugation by 3-Wave
               and 4-Wave Mixing."

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